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XIII.

ON THE CHARGING OF CONDENSERS BY GALVANIC BATTERIES.

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Presented March 13, 1889.

I. THE USE OF WATER CELLS.

THE different methods which are commonly used for comparing the capacities of condensers often lead to widely different results.

Several condensers may be apparently of the same capacity when tested by one process, while each differs from all the others under a second set of conditions. Every condenser has its own characteristics, and these must be specially studied before it can be used in accurate work.

The present investigation grew out of the discordant results which one of us obtained in attempting to compare condensers made in different ways. Our experiments have removed some of our own difficulties, and we think that an account of our work may prove useful to others.

We shall begin by considering the behavior of different batteries when they are suddenly called on to furnish definite quantities of electricity in definite short times, and in this first paper we shall give some results which we have obtained in using water cells.

These results are interesting, because the water battery possesses in an exaggerated degree some properties which are common to all batteries, and which may seriously affect* the quantity of electricity furnished to a large condenser by a cell with which it is connected for a short time only.

The cells that we used were made of ordinary " $2\frac{1}{2}$ ounce wide mouth flint glass bottles," filled to the neck with faucet water, and containing each a strip of zinc and a strip of copper placed vertical and nearly parallel to each other, at a distance apart of about two centimeters. The cylindrical part of each bottle under the neck was about six centimeters high, and four centimeters in diameter, and each strip of metal was of such a size as to expose a surface of seven square centimeters on each of its sides to the liquid. The resistance of each cell as measured by the use of alternating currents* was nearly 1200 ohms. Of a large number of such cells at our disposal, we found 240 sufficient for our purpose, and a switch-board enabled us to arrange these easily in various combinations of groups of twenty cells each.

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* Von Beetz, Wied. Ann., xxvi. p. 24, 1885.

The condensers which we used in this part of our work were nine in number, including one of a capacity of one microfarad subdivided into fractional parts. This condenser, which was made by Messrs. Elliott Brothers and marked by them No. 72, we took as a standard.

As we shall show when we come to discuss the characteristics of different condensers, the ratios of the capacities of the other condensers to the capacity of this one varied somewhat with the time of charging, but, when this remained constant, were the same, whatever the kind of battery used.

The capacity of each of the condensers for each time of charging was measured in terms of the capacity which No. 72 has when charged for one second by a battery of small internal resistance. The capacities of five of the other condensers, as determined in the manner just described, did not vary on the average by more than two per cent when the time of charge was decreased from 2.0 seconds to 0.01 second, that is, in the ratio of 200 to 1. By combining the different condensers, we were able to get within one twentieth of a microfarad any capacity from 0 to 11 mf., a range which was amply sufficient for our purposes.

Most of our work on water cells was done with the help of a four-coil mirror galvanometer (A), of 3300 ohms' resistance. For some purposes, however, only one of the coils was used. The period of the complete swing of the galvanometer needles was 27 seconds, and the ratio of two successive swings 1.058. Unlike some of our other galvanometers, this one, when used ballistically, within the limits which we set for our experiments, gave throws which seemed to be functions only of the quantity of electricity† discharged through it, that is, independent of the tension of this electricity at the instant of discharge. A minute coil of wire, placed in the core of one of the galvanometer coils, through which by means of a double key the current from a small thermopile could be sent in either direction, served to damp the oscillations of the needle after a throw had been given.

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* F. Kohlrausch, Wied. Ann., xi. p. 653, 1880.

† See Lord Rayleigh, Phil. Trans., Pt. 2, p. 619, 1882.

A few of our measurements were made with the help of another four-coil galvanometer (B), of 3000 ohms' resistance. The period of a complete swing of its needle was 52.7 seconds, and the ratio of successive swings 1.068. With scale placed at a distance of one meter from the mirror, one microcoulomb when discharged through this galvanometer gave a throw of 45 mm.

For intervals between 0.01 sec. and 0.5 sec., the apparatus shown in Figure 1 was used. It consists of a pendulum with an iron bob, A, eight inches long, two inches in diameter, and weighing 7 lb., and a brass rod $\frac{1}{2}$ inch in diameter weighing 2.8 lb. The axis of suspension is formed by a brass rod $2\frac{1}{2}$ inches long held between pointed screws.

Upon this axis and concentric with it are placed two ebonite disks, F, 6 inches in diameter and $\frac{3}{8}$ inch thick. The face of each of these disks is armored through about half of its circumference with a strip of German silver $\frac{1}{32}$ inch in thickness, held by rivets passing through the disk, and the edge of the armature is turned true with the edge of the disk.

The disks are placed with their armored faces adjacent, but separated by an ebonite washer 5 inches in diameter and $\frac{1}{32}$ inch in thickness. One of the disks is fixed to the pendulum rod, while the other can be revolved about their common axis so that the two German silver strips may overlap to any desired extent; the arc *a*, attached to the movable disk, serves to clamp the two disks firmly together, and also to determine approximately the amount of the overlapping. To each of the German silver strips is joined a wire, *b*, which dips in a mercury cup, *g*, connected with one of the two points between which the circuit is to be made; to avoid as far as possible any interference with the motion of the pendulum, these mercury cups are placed very close to the axis of suspension.

The pointed screws upon which the pendulum swings are held in a frame, *c c*, of wrought iron, which is itself swung between two pointed screws, *d d*, perpendicular to the axis of suspension of the pendulum. By rotation of the frame *c c* upon these screws, the axis of the pendulum is easily levelled.

To the frame *c c* is attached a pillar, *e*, carrying a copper wire, *f*, $\frac{1}{20}$ of an inch in diameter, in such a position that its end runs with

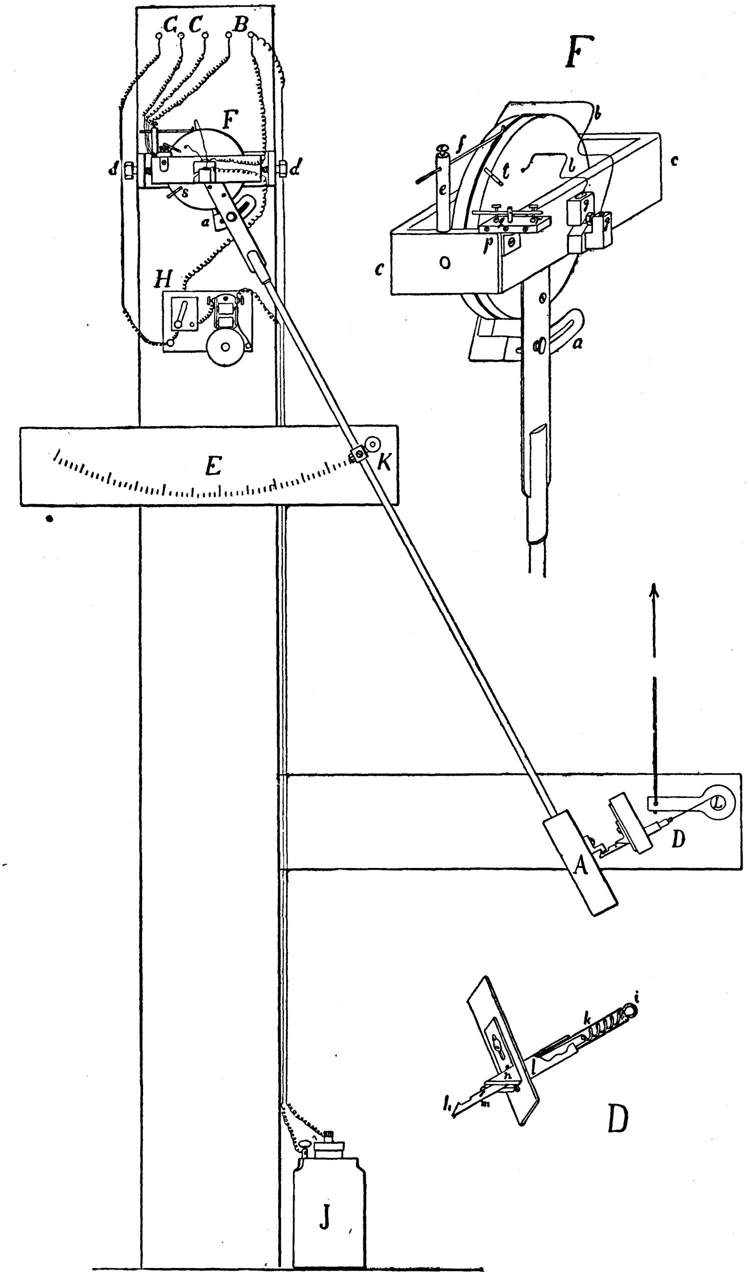


Fig. 1.

light friction in the narrow groove between the two disks as the pendulum swings; both the end of the wire and the sharp edges of the disks are somewhat rounded to prevent undue wear. If the two disks are clamped together in a position such that the unarmored part of one is opposite the armored part of the other, and that as the pendulum swings the wire leaves one German silver strip just as it reaches the other, it will be in contact with each armature successively, but will establish metallic contact between them and close the circuit between the mercury cups at most for a very short interval; if, however, the armatures overlap for a certain number of degrees, contact will be maintained while the pendulum swings through just that number of degrees of its arc. The front disk, which is rigidly fixed to the pendulum rod, is so placed that it comes in contact with the copper wire just as the pendulum reaches its lowest point. If therefore the armatures overlap, for instance, 10°, and if the pendulum is drawn out to a known point upon one side of its arc so that the copper wire rests upon the unarmored side of the "fixed" disk, then, when the pendulum is allowed to fall, metallic connection will exist between the disks while it is rising through 10° from its lowest point. From this "arc of contact" the time of contact is easily determined. The time of vibration of the pendulum is 1.181 sec., and the arc of initial displacement 28° 56′; the decrease of arc in one complete vibration is about 30′.

The length of the arc of contact may easily be determined within one minute. This uncertainty may give rise to an error in the computed time varying from 0.00022 sec. for an arc of 1°, to 0.00042 sec. for an arc of 25°.

The errors arising from a wrongly assumed value of the initial displacement, and from decrease of arc, are in no case greater than one fourth of one per cent of the computed time, and are here neglected.

Since the copper wire does not touch each of the armatures in a single point, the arc of contact will obviously not be exactly equal to the angle of overlap, but its value may be easily determined by direct observation. By throwing the switch at H to the right, the circuit through the bell and battery, J, is made complete, except for the break at the disks. The pendulum is then lowered, and the readings on the divided arc E of the microscope K are noted when the bell begins and stops ringing, as the pendulum is moved through its ascending arc; the former must nearly correspond with the reading when the pendulum is in its position of rest. To facilitate this latter adjustment the wire *f* is made movable in the direction of its length.

For releasing the pendulum and catching it at the end of its spring, the contrivance shown at D is used. The latch *h* is firmly fastened to the spring *i*, which serves the double purpose of giving the upward force upon the latch-bar to cause it to engage with the catch upon the pendulum bob, and also of lessening the shock produced upon the whole apparatus by the arrest of the pendulum. The spring *i* is fixed inside the tube *k*, which, sliding inside the sleeve *l*, serves as guide and stop for the motion of the latch. To operate the mechanism, the tube *k* is drawn out by the cord attached, and the pendulum drawn with it by the latch; at a certain point, however, the pin *m*, which passes through the latch, is brought against the wedge *n*, and a slight further motion trips the latch, and the pendulum is released. The point at which the pendulum is released is so adjusted, by sliding the wedge *n*, that the arc through which the bob is lifted is slightly greater than the loss of the arc through friction, etc. in a complete vibration. The latch is drawn up by a cord passing around an axis, L, which is turned by a lever and cord pulled by the observer at the galvanometer. This is to insure that the pendulum is dropped from nearly the same height at each observation, the multiplying arrangement serving to decrease the velocity with which the pendulum is raised, so that it rises an exceedingly small distance beyond the point where the latch is tripped. As soon as the pendulum falls, the latch, being at once released by the observer, is drawn back to its lowest position by a spring, not shown in the figure, and the pendulum returning is caught by the latch, and thus, having made a complete swing, is left in its original position ready for the next observation.

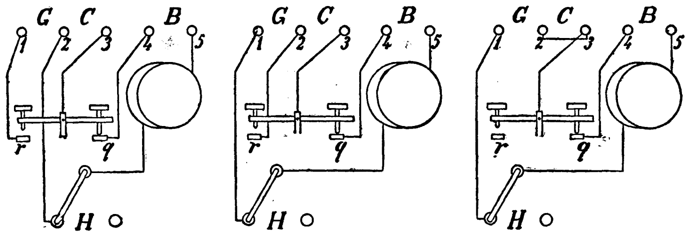
Attached to the frame in which the pendulum swings is a balanced rocking key, *p*, with two adjustable screws making contact in mercury cups. When the pendulum hangs by the latch, the key rests in contact with the left-hand mercury cup *q*, through the left-hand screw; but as the pendulum completes its half-vibration, the pin *s*, attached to the "fixed" ebonite disk for this purpose, throws the lever over upon the right-hand contact, *r*, where it remains during the second half-vibration of the pendulum, being replaced in its original position by the pin *t*, as the pendulum is caught by the latch.

The cycle of operations performed by the pendulum is explained by the diagram below, which shows the connections as made for the three different kinds of observation: —

(1.) Charge of the condenser for a short measurable interval followed by discharge through the galvanometer, the discharge occurring about 0.6 sec. after the commencement of the charge, and the contact between condenser and galvanometer lasting about 1.2 sec.

(2.) Charge of the condenser through the galvanometer for a short measurable interval; discharge (not measured) about 1.8 sec. after commencement of charge, the condenser remaining short-circuited 1.2 sec. This is the arrangement shown in Fig. 1.

(3.) Current flowing directly through the galvanometer for a short measurable interval of time.



I. II. III.

Fig. 2.

The switch H is always turned to the left except when the arc of contact is to be measured as before described.

For all the observations on condensers referred to in this paper, the first figure is applicable ; the action is then as follows.

When the pendulum rests in the latch, one terminal of the condenser, C, attached to the binding screw 3, is in connection, through the rocking key, with the mercury cup, *q*, and therefore with one pole of the battery, B, at 4. When the pendulum is released, contact is made between the disks during a certain arc of swing, and the current then flows from the binding screw 5, through the disks and switch H, to the other terminal of the condenser at 2.

On the pendulum's arriving at the end of its swing, the key is shifted from contact with 4 to contact with 1, causing the condenser to be discharged through the galvanometer; returning, the pendulum returns the rocking key to its initial position, ready for the next observation. It may be noted that the battery is permanently connected with one pole of the condenser except during the return swing of the pendulum, but we have found no trouble from leakage in these experiments. The action in cases (2) and (3) will be sufficiently evident from the above description.

The weight of the pendulum rod being considerable, we found that it was somewhat bent by its own weight when the pendulum bob was supported by the latch, and when released a vibration was set up in the rod on its own account, which caused a rapid vibration of the disks in addition to the motion due to the pendulum. The result of this was to produce an uncertainty in the beginning and end of contact, depending upon the relative phase of the two vibrations at the beginning and end of the arc of contact; the amount of this uncertainty was less than 0.0005 sec., and was greatly lessened by adding steel wire stays to the rod when it became desirable to use the pendulum for times approaching 0.001 sec. in magnitude.

A similar effect, probably attributable to the same cause, was noticed as producing a considerable error in a much larger pendulum of similar construction, when used for times approaching 0.001 sec., although the rod was of wood 1⅞ inches square in section, the bob weighing 40 lb. and the time of swing being 1.8 sec., with an initial displacement of 26°.

We have used a more simple apparatus, shown in Fig. 3, in cases where it was desired to charge a condenser for a definite interval of time, the absolute value of which is required to be known with a higher degree of accuracy. With the pendulum already described, the time is liable to considerable error when determined by an arc of contact nearly equal to the half arc of swing; that is, when the time of contact is in the neighborhood of 0.5 sec.

Where different times are not to be experimented upon, a greater degree of accuracy may be attained if the contact existing through the upward swing be maintained through the downward swing as well, beginning and ceasing nearly at the lowest point of the swing. The time of contact is then equal to the time of vibration, affected by a very small correction, which depends upon the departure of the beginning and end of contact from the lowest point, and which may be determined with considerable accuracy.

The pendulum bob is of iron, and is held displaced from its position of rest by one pole of a horseshoe magnet *b*, in contact with it at its middle point; this magnet is attached to the plate *c*, which turns on the screw *d*, so that the magnet may be moved in the plane of vibration of the pendulum by a cord leading to the observer at the galvanometer. The pin *e* acts as a stop limiting this motion of the

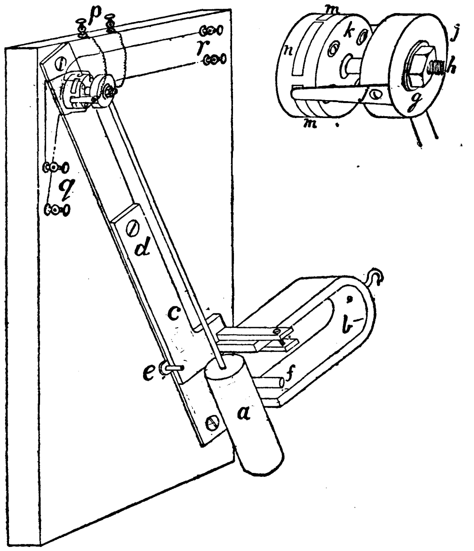


Fig. 3.

magnet towards the left. If the magnet is pulled out a certain distance toward the right, the pendulum bob is brought against the stop *f*, and any further motion of the magnet detaches the pendulum; the magnet is at once released by the observer, and falls back to a point fixed by the stop *e*, so as to arrest the pendulum at the completion of its first swing. The pendulum rod is screwed into the edge of an ebonite disk, *g*, three eighths of an inch thick and one inch in diameter, through the centre of which passes the pin *h*, which forms the axis of suspension. Attached to the disk *g* are two copper strips, *j*, of which one is shown in the figure, and which, as the pendulum swings, rub lightly upon the edge of the fixed disk *k*. Inserted in the latter are four pieces of copper *m*, *n*. In the ordinary position of the pendulum as shown in the figure, the copper strips *j j*, which are connected with the condenser by the binding screws at *p*, rest upon the opposite copper pieces *m m*; and through them are in circuit with the binding screws at *q*, which are connected with the galvanometer. The condenser is thus short circuited through the latter.

When the pendulum swings, the strips *j j* make contact at the lowest point of the swing with *n n*, which are connected through the binding screws at *r* with the battery; and this connection is maintained until the pendulum reaches its lowest point on the return swing, when the strips *j j* pass to the copper pieces, and the condenser is discharged through the galvanometer. It is hardly necessary to say, that the width between the pieces *m* and *n* is made slightly greater than the width of *j*, to prevent a direct current from the battery through the galvanometer.

The method above described has been found very satisfactory for the purpose of obtaining a single swing of a not too heavy pendulum; it is essential that the stop *e* should be somewhat elastic; a short piece of soft rubber tubing slipped over the pin answers well.

The upper pole of the magnet is brought quite near the upper part of the pendulum bob to strengthen the induction.

The motion of the magnet is so slight, that its direct effect upon the galvanometer is negligible. No great care is necessary in the release, as, even if the bob is brought up against the stop *f*, so as to rebound, the time of describing the second and third quarters of the complete vibration is altered by an inappreciable amount.

With the apparatus described a great many measurements were made, and these all gave concordant results. The following tables give, in microcoulombs, the charges which variously arranged batteries of water cells gave, in the times named, to condensers of different capacities. Each number in the body of a table is the mean of a set of closely agreeing observations. In the cases of many of the combinations of cells we have used a much greater number of different capacities than is indicated in the tables, but the results given below are representative.

Whereas in studying certain other cells we have found it desirable to use times shorter than the ten-thousandth of a second, it is evident, from the results in Table I., that in the present instance it was not worth while to use charging times smaller than the hundredth of a second.

TABLE I.

Quantity of Electricity delivered in 0.01 *seconds by different Batteries of Water-cells to Condensers of various Capacities.*

Battery.	Capacities of Condensers in Microfarads.						
	0.1	0.3	0.5	1.0	1.87	3.06	9.58
	mc.	mc.	mc.	mc.	mc.	mc.	mc.
20 cells in series	0.9	1.0	1.0	1.1	....	....	1.1
4 parallel 20's	....	....	3.1	3.4	....	3.8	4.0
8 parallel 20's	1.6	3.5	4.6	5.8	6.3	6.8	7.9
12 parallel 20's	1.7	4.2	5.8	7.9	9.1	9.7	10.8
6 parallel 40's	2.6	4.6	5.2	5.3	5.5	5.5	5.8
60 cells in series	1.1	1.2	....	1.3	....	....	1.3
4 parallel 60's	....	3.5	3.5	3.8	4.1	4.4	4.4
3 parallel 80's	....	3.0	....	3.3	....	3.3	3.6
2 parallel 120's	2.4	....	2.6	2.7	....	2.8	3.2
240 cells in series . . .	2.4	....	....	2.7	....	2.7	2.8

TABLE II.

Quantity of Electricity delivered in 0.19 *seconds by different Batteries of Water-cells to Condensers of various Capacities.*

Battery.	Capacities of Condensers in Microfarads.					
	0.5	1.0	1.87	3.06	6.82	10.70
	mc.	mc.	mc.	mc.	mc.	mc.
20 cells in series . .	5.4	7.3	8.7	8.9	9.6	9.6
3 parallel 20's . .	7.2	12.3	17.1	20.1	23.8	25.3
12 parallel 20's . .	8.2	15.9	28.7	42.7	69.6	82.5
40 cells in series . .	7.1	8.4	8.8	9.6	....	9.8
6 parallel 40's . .	14.2	25.5	37.1	44.1	53.0	55.9
60 cells in series . .	7.6	8.9	9.1	9.0	....	9.6
4 parallel 60's . .	18.5	26.6	31.0	35.7	38.5	40.1
3 parallel 80's . .	18.7	24.6	26.7	29.7	30.3	31.0
2 parallel 120's . .	17.3	19.0	20.1	20.7	....	21.5
240 cells in series .	10.9	11.2	11.3	11.3	....	11.8

TABLE III.

Quantity of Electricity delivered in 0.37 *seconds by different Batteries of Water-cells to Condensers of various Capacities.*

Battery.	Capacities of Condensers in Microfarads.					
	0.5	1.0	1.88	3.07	6.86	10.85
	mc.	mc.	mc.	mc.	mc.	mc.
20 cells in series . .	7.1	10.9	13.0	15.1	17.4	17.4
2 parallel 20's . .	8.0	14.0	20.6	26.0	31.8	33.9
3 parallel 20's . .	8.1	14.6	24.1	31.7	42.3	46.8
4 parallel 20's . .	8.1	15.5	....	38.0	55.6	64.5
6 parallel 20's . .	8.6	16.6	....	43.6	70.5	83.0
8 parallel 20's . .	9.0	16.7	30.3	46.8	80.4	98.9
12 parallel 20's . .	....	17.0	31.7	50.3	94.8	119.3
40 cells in series . .	10.8	13.3	16.4	17.5	18.9	20.0
2 parallel 40's . .	14.6	22.4	29.2	32.9	37.0	39.2
3 parallel 40's . .	15.0	25.1	36.2	43.2	50.3	52.6
4 parallel 40's . .	16.4	28.1	42.4	52.1	66.7	71.6
5 parallel 40's . .	....	29.6	46.4	60.3	78.2	85.5
6 parallel 40's . .	16.6	31.6	51.5	68.2	91.3	100.2
60 cells in series . .	12.0	14.9	....	....	....	19.2
2 parallel 60's . .	18.5	26.2	....	....	....	38.4
3 parallel 60's . .	20.8	32.9	....	49.3	54.4	57.5
4 parallel 60's . .	22.8	38.3	52.9	63.2	73.0	77.0
80 cells in series . .	14.1	16.6	18.7	19.8	20.0	20.7
2 parallel 80's . .	22.1	29.0	33.9	36.2	38.9	39.5
3 parallel 80's . .	26.1	39.1	47.4	53.5	58.6	62.1
120 cells in series .	16.4	17.8	19.1	20.2	20.4	20.7
2 parallel 120's . .	26.2	33.6	37.3	38.8	41.0	42.4
240 cells in series .	18.9	20.2	....	21.9	21.7	

TABLE IV.

Quantity of Electricity delivered in 0.93 seconds by different Batteries of Water-cells to Condensers of various Capacities.

Battery.	Capacities of Condensers in Microfarads.					
	0.5	1.0	1.89	3.11	7.18	11.41
	mc.	mc.	mc.	mc.	mc.	mc.
20 cells in series .	7.2	13.0	19.2	24.6	29.6	32.2
3 parallel 20's . .	7.3	14.2	....	38.6	61.8	72.8
6 parallel 20's . .	7.6	....	....	46.3	89.7	
12 parallel 20's . .	....	16.1	....	51.0	103.9	
40 cells in series . .	14.4	21.5	26.2	28.9	....	32.9
6 parallel 40's . .	16.0	31.1	56.8	84.6		
80 cells in series . .	21.0	27.6	32.9	35.1	36.5	37.0
3 parallel 80's . .	29.7	50.7	71.7	85.3		
120 cells in series .	24.3	30.0	33.5	34.1	....	36.3
2 parallel 120's . .	35.6	51.1	61.9	68.2	72.3	74.1
240 cells in series .	31.6	34.9	37.2	37.9	....	39.0

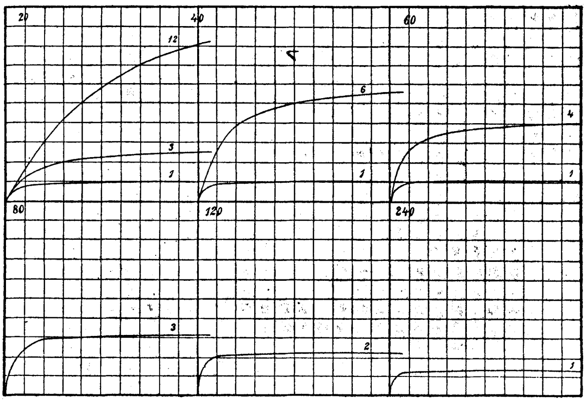
TABLE V.

Quantity of Electricity delivered in 2.0 seconds by different Batteries of Water-Cells to Condensers of various Capacities.

Battery.	Capacities of Condensers in Microfarads.					
	0.5	1.0	1.89	3.11	7.19	11.74
	mc.	mc.	mc.	mc.	mc.	mc.
20 cells in series . .	7.3	14.4	24.9	35.1	52.9	57.7
2 parallel 20's . .	....	14.3	26.8	42.3	75.5	93.8
4 parallel 20's . .	....	15.2	....	48.8	96.1	
40 cells in series . .	14.8	26.2	40.0	50.1	59.3	64.1
2 parallel 40's . .	....	30.1	51.4	72.6		
4 parallel 40's . . .	....	31.0	56.7	87.6		
60 cells in series . .	20.0	33.1	....	53.6	62.3	65.0
3 parallel 60's . . .	....	44.5	77.1			
80 cells in series . .	25.8	40.8	53.6	59.8	68.5	69.8
2 parallel 80's . .	28.5	53.0	78.7	97.4		
3 parallel 80's . .	30.4	58.2	94.2			
120 cells in series .	33.8	47.4	57.8	63.9	71.9	75.6
2 parallel 120's . .	....	73.5	100.0			
240 cells in series .	49.8	63.6	71.0	78.0	....	83.8

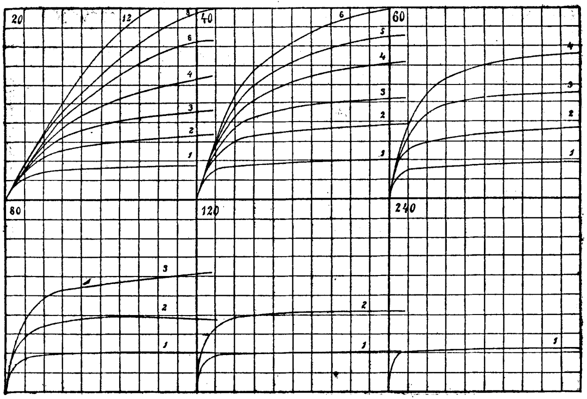
The results given in Tables II., III., IV., and V. have been used in plotting the subjoined curves. In each curve the ordinates represent the charges on a scale of 10 microcoulombs to a division, and the abscissas represent the capacities of the charged condensers in microfarads. Attached to each curve is a number (*m*), and at the upper left-hand corner of the square in which the curve is drawn is another number (*n*). These denote that a battery made up of *m* parallel groups, each consisting of *n* cells in series, was used in obtaining the results from which the curve has been plotted.

FIG. 4.



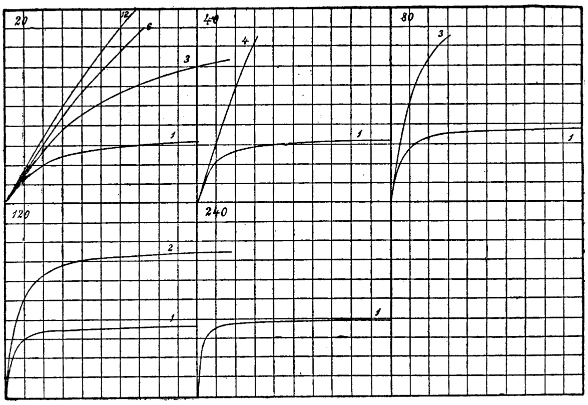
Time of charge, 0.19 sec. Unit of abscissas, 1 mf. Unit of ordinates, 10 mc.

FIG. 5.



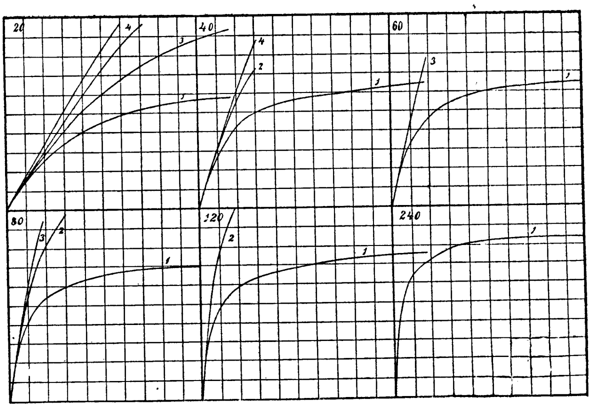
Time of charge, 0.37 sec. Unit of abscissas, 1 mf. Unit of ordinates, 10 mc.

Fig. 6.



Time of charge, 0.93 sec. Unit of abcissas, 1 mf. Unit of ordinates, 10 mc.

Fig. 7.



Time of charge, 2 sec. Unit of abscissas, 1 mf. Unit of ordinates, 10 mc.

It will be noticed that all the curves in all those squares which have any one number in their upper left-hand corners, have the same slope at the origin. This slope is numerically equal to one tenth* of the electromotive force in volts of the charging batteries, as computed from measurements of such cells in open circuit made with a Quadrant Electrometer.

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* Each vertical unit corresponds to ten microcoulombs.

So far as we can judge from our observations with limited capacities, each curve has as an asymptote a line parallel to the axis of x, and at a distance from it which represents the quantity of electricity which the charging battery would yield if joined up for the time given in simple circuit with a trifling outside resistance. Direct experiment shows that this quantity is almost exactly proportional to the number of cells joined up parallel to each other.

The general effect of interposing a large resistance wound bifilar between the battery and the condenser which it is charging is shown by the following diagram, in which the curves are drawn in the same way as in Figures 4, 5, 6, and 7. The two upper curves represent observations taken with a battery of twelve parallel groups of 20 water cells each, first with no interposed resistance and then with 247,000 ohms inserted. The two lower curves represent similar observations made with a single group of 20 cells joined up in series.

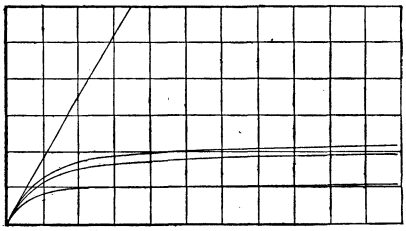

FIG. 8.

For purposes of comparison with the numbers in Tables I., II., III., IV., and V., we give some results obtained with a battery consisting of 20 water cells arranged in series. The poles of this battery were connected together, through various outside resistances, for given short intervals of time, and the quantities of electricity which traversed the circuit during these intervals were measured.

The three curves of Fig. 9 were plotted by using as abscissas the times * during which the battery circuit was closed, and as ordinates the quantities of electricity which passed through the circuit in these times. The observations represented by points in the upper curve were made when the resistance in the circuit outside the battery was 3,000 ohms. The corresponding resistances for the other two curves were 102,000 ohms and 250,000 ohms respectively. It will be

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* Each vertical unit corresponds to 1 microcoulomb. Each horizontal unit corresponds to 0.01 sec.

noticed that the curvature near the origin is considerable, but that after about one tenth of a second each line becomes nearly, though not quite, straight. If the internal resistance of the battery is assumed to be 24,000 ohms, the effective electromotive forces in the circuit after one tenth of a second are about 1.2 volts, 4.5 volts, and 7.4 volts, respectively. The electromotive force of the open battery was a little over 16 volts.

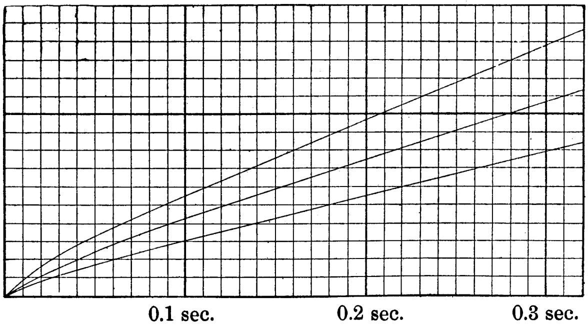

Fig. 9.

The results in Table VI. were obtained with another battery of 20 water cells which had been resting for one month. The numbers in the body of the table give in microcoulombs the quantity of electricity which passes through the circuit when the poles of the battery were connected for the times named through various external resistances.

TABLE VI.

Duration of Current.	Resistance of Outside Circuit in Ohms. 3,000	102,000	250,000
sec.	mc.	mc.	mc.
.0025	0.34	0.21	0.12
.011	0.94	0.59	0.41
.034	2.50	1.73	1.22
.077	4.94	3.59	2.52
.1033	6.43	4.64	3.34

After the poles of a battery of these water cells joined up in series have been connected together for a short interval only (say for one second or less), the battery seems to regain almost instantly its original electromotive force. Indeed, it is evident from the numbers given in Tables I., II., III., IV., and V., that the polarization — which, as is well known, increases and diminishes in the case of any given simple element with the intensity of the currents which pass through the cell — must almost instantly respond to any decrease in the density of the current. Of course, if a battery of water cells is short-circuited for a number of seconds or minutes, the polarization slowly increases, and the battery becomes " tired," and after the circuit is broken it must be allowed to rest for a number of minutes, or even hours, before it gets back its lost power.

From the fact that the lines in Fig. 9 are not straight, it appears that the sudden falling off in the electromotive force of the cells when the circuit is closed is not wholly due to a polarization, which is at every instant simply proportional to the density of the current then flowing.

We shall not discuss further the subject of polarization in water cells until we have published the results of some observations made with other kinds of battery.

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